A Case Study of Internal Solitary Wave Propagation During ASIAEX 2001

Antony K. Liu, Steven R. Ramp, Yunhe Zhao, and Tswen Yung Tang

***Abstract*—During the recent Asian Seas International Acoustics Experiment (ASIAEX), extensive current meter moorings were deployed around the continental shelf-break area in the northeastern South China Sea. Thirteen RADARSAT SAR images were collected during the field test to integrate with the *in situ* measurements from the moorings, ship-board sensors, and conductivity/temperatire/depth (CTD) casts. Besides providing a synoptic view of the entire region, satellite imagery is very useful for tracking the internal waves, locating surface fronts, and identifying mesoscale features. During ASIAEX in May 2001, many large internal waves were observed at the test area and were the major oceanic features studied for acoustic volume interaction. Based on the internal wave distribution maps compiled from satellite data, the wave crests can be as long as 200 km with an amplitude of 100 m. Environmental parameters have been calculated based on extensive CTD casts data near the ASIAEX area. Nonlinear internal wave models have been applied to integrate and assimilate both synthetic aperture radar (SAR) and mooring data. Using SAR data in deep water as an initial condition, numerical simulations produced the wave evolution on the continental shelf and compared reasonably well with the mooring measurements at the downstream station. The shoaling, turning, and dissipation of large internal waves at the shelf break have been studied and are very important issues for acoustic propagation.**

***Index Terms*—Internal waves, remote sensing, shallow water.**

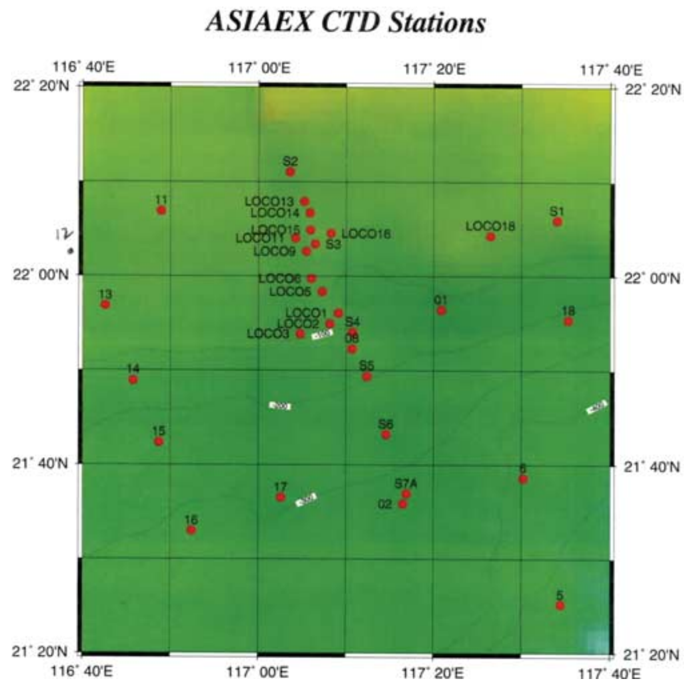

Fig. 1. CTD stations collected from the *Ocean Researcher 1* during the ASIAEX 2001 field program in the SCS.

I. Introduction

An OCEAN current flowing over topographic features such as a sill or continental shelf in a stratified flow can produce nonlinear internal waves of tidal frequency and has been studied by many researchers [1]–[3]. Their observations provide insight into the internal solitary wave-generation process and explain the role that they play in the transfer of energy from tide to ocean mixing. It has been demonstrated that surface signatures of these nonlinear internal waves are observable in synthetic aperture radar (SAR) images [4] from the Russian *Almaz-1* and from the First and Second European Remote Sensing Satellites (ERS-1/2) [5]. Recently, the internal solitary wave distribution maps in the northeastern South China Sea (SCS), near Hainan Island, have been compiled from hundreds of ERS-1/2, RADARSAT, and Space Shuttle SAR images from 1993 to 1998 [6]. Based these maps, most of internal waves in the northeastern part of SCS are propagating westward. The wave crests can be as long as 200 km with amplitude of 100 m, due to strong current from the Kuroshio branching out into the SCS [7]. From the observations at drilling rigs near DongSha Island by Amoco Production Co. [8], the solitons may be generated in a 4-km-wide channel between Batan and Sabtang Islands in the Luzon Strait. However, recent work [7], [9] has suggested that solitons in the SCS may also be generated locally near the Chinese continental shelf break. Furthermore, based on satellite imagery, the long-crested internal waves near Luzon Strait are produced by the connection along the crest of many individual wave packets generated from different sources or sills in the strait [10].

The essential element of the surface/internal wave interaction is between the internal wave-induced surface current field and the wind-driven ocean surface waves. For a linear SAR system, the variation of the SAR image intensity is proportional to the gradient of the surface velocity or to the strain rate. This proportionality depends on radar wavelength, radar incidence angle, angle between the radar look direction and the internal wave propagation direction, azimuth angle, and the wind velocity [4]. For the high-wind-speed condition, the internal wave signal may be too weak to be observed by radar due to low signal-to-noise ratio (SNR). When the internal waves propagate in the cross-wind direction, the wave-current interaction also is relatively weak and so is the radar backscattering for SAR observation. The strain rates have been previously calculated for the internal wave packets in the New York Bight and their values are consistent with the observed data [3]. Lacking *in situ* field

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measurements for detailed comparisons with the numerical simulations, one can only say that the relative modulation from the SAR data and the strain rate from the model agree reasonably well qualitatively [7].

The 1995 Shallow Water Acoustics in a Random Medium (SWARM) experiment demonstrated that internal waves are responsible for the anomalous frequency response of shallow-water sound propagation [11]. Based on data and acoustic model analysis, the acoustic impact was due to resonant acoustic mode coupling, which in turn was strongly affected by the number of solitons per packet, their location, the direction of propagation, and wavelength.

In 1997, U.S. and Asian Pacific Rim scientists began planning a joint effort to design and conduct an experiment to study shallow-water acoustics, physical oceanography, and bottom structure in the South and East China Seas. This experiment, called the Asia Seas International Acoustics Experiment (ASIAEX), started in 1999 with a series of field tests in the SCS survey area [12] in conjunction with modeling and remote-sensing studies. In April 2000, five moorings were deployed for 1 mo while the available SAR coverage was collected and processed at the Taiwan ground station in near real time [13]. This work revealed the very large-amplitude internal wave field propagating west–northwest (WNW) across the SCS and was very useful in planning for the primary effort during spring 2001.

The ASIAEX 2001 major experiment focused on acoustic volume (i.e., water column) interactions, as opposed to the ASIAEX ECS experiment, which emphasized boundary (sea surface and bottom) interactions. The field work was conducted during seven cruises on the Taiwanese research vessels *Ocean Researcher I*, *Fisheries Researcher I*, and *Ocean Researcher III*. The moorings were in the water between April 29 and May 14, 2001 [15]. Extensive conductivity/temperatire/depth (CTD) and SeaSoar towed vehicle surveys were conducted while the moorings were in the water [16]. During the field test, typhoon Cimaron passed through the ASIAEX area around May 12. Based on the observations from SAR, SeaSoar, and mooring data, the internal waves and tides dominated the oceanic variability in the ASIAEX area. In this paper, the SAR and *in situ* observations during ASIAEX 2001 used in this case study will be described first. Next, the SAR and mooring data are compared to extract the critical internal wave parameters. Then, the evolution model of nonlinear internal waves on the continental shelf is formulated and numerical simulations are performed for comparison. The internal wave characteristics near the ASIAEX area are summarized to conclude this paper.

VII. Summary and Discussion

In this case study, nonlinear internal wave evolution in the northeast sector of the SCS has been analyzed based on the ASIAEX SAR, CTD, and mooring data. Selective sets of mooring data concurrent with the SAR observations are presented and analyzed for the parametric study of internal wave characteristics. Based on the results from the SAR and mooring data in Table II, the environmental conditions and typical internal wave characteristics near the ASIAEX area on May 10, 2001, from deep mooring S8 to shallow mooring S4 can be summarized as follows:

- water depth decreased from 800 to 70 m across the slope and shelf;
- internal wave propagation direction rotated clockwise from 295° to 345°;
- wave speed decreased from 1.8 m s^{-1} to 0.72 ms^{-1};
- estimated soliton width ranged from 1.6 to 0.7 km;
- number of solitons per packet varied between 5–3;
- soliton separation distance (wavelength) ranged from 9.7 to 1.2 km;
- theoretically estimated amplitude ranged from 95 to 63 m and less in shallow water.

These observations have provided a calibration on SAR data and inputs for the numerical simulation of nonlinear wave evolution on the continental shelf. These observations, extracted scale parameters, and wave characteristics should be useful for calibration a variety of nonlinear internal wave evolution models.

The mesoscale variability, mean horizontal and vertical shears, and varying stratification near the shelf break were highly transient in April/May during the spring transition from winter monsoon to summer typhoon season. Therefore, the evolution of internal solitons in the ASIAEX test area at the shelf break is especially complicated in April/May, with many interesting features such as the mode-2 solitons [12]. Therefore, the solitons are in transition with continuous evolution and dissipation along the shelf in this late spring season. During ASIAEX, nonlinear internal waves propagating up the slope have also been tracked by a research ship [20] equipped with tow-yo CTD, ADCP, and acoustic flow visualization systems. These instruments have observed conversion of depression internal solitary waves to elevation waves. The location of the initiation of the depression to elevation conversion was identified in their high-resolution acoustic data. Their data provide additional information concerning the shoreward evolution of the soliton packets.

It is clear that these internal wave observations near the ASIAEX area provide a unique resource for addressing a wide range of processes on solitary wave propagation up the slope. Among these the following are included:

- disintegration of solitons into internal wave packets, breaking, and dissipation;
- shoaling effects of variable bottom topography on wave evolution, generation of mode-2 waves, and internal wave–wave interaction;
- evolution of nonlinear depression waves through the critical depth to become elevation waves.

Numerical simulation has been performed by using the SAR-observed internal wave field in the shelf break region as an initial condition to simulate the wave evolution. The numerical simulation compares reasonably well with the measurements at the downstream mooring S5 on shelf for three solitons in a large wave packet as regards their amplitudes, wavelengths, and wave speeds. This case study of numerical simulation demonstrates the method of data assimilation to integrate all data from SAR, moorings, and CTD casts. The simulations, which are continuous in space and time, provide a means to characterize the waves for comparison with acoustic propagation-loss models.